32.1: *Invited Paper:* A Comparison of Pixel Circuits for Active Matrix Polymer/Organic LED Displays

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Abstract

In this paper measurements on several types of active matrix polymer LED (AMPLED) displays will be presented. The issues of image uniformity and polymer aging will be addressed by pixel circuit designs.

1. Introduction

Polymer LED's provide a new alternative to LCD's for many display applications, and are particularly attractive because of their high brightness, near-perfect viewing angle, and very fast response time.

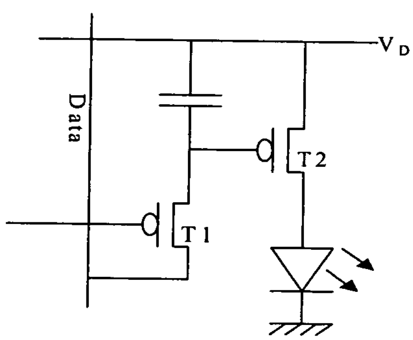

Figure 1 - Current Source Pixel Circuit

A basic form of pixel addressing circuit for current driven devices was first discussed by Brody in 1975 [1], and is shown schematically in figure 1. The use of Polymer LEDs for electroluminescent displays has two main advantages over organic LED displays namely the lower driving voltage and fabrication using simple printing techniques. However, both polymer and organic LEDs suffer aging effects and uniformity problems when driven with an active matrix. It is the purpose of this paper to examine the issues of image uniformity and LED aging.

2. Image Uniformity

The current source pixel circuit shown in figure 1 is a simple circuit but is susceptible to variations in the threshold voltage and mobility of transistor T2. Low temperature Poly-Silicon (LTPS) Thin Film Transistors (TFTs) suffer point to point variations in their threshold voltage and mobility due to the random variations in the silicon grains formed when annealing. This appears to be inherent in all forms of LTPS. The variations in these parameters mean that a given gate-source voltage for T2 in figure 1 will result in different currents for different pixels. This in turn results in random variations in brightness between different pixels. The result is images containing random noise. For this 'noise' to be invisible to the user the percentage current variation of the TFT with respect to its threshold voltage and mobility must be below 2% [2]. Using the simple quadratic law for a MOSFET ($I=\beta(V-V_T)^2/2$) we can show that the percentage current variation $\sigma(I)/I$ with respect to the threshold voltage variation $\sigma(V_T)$ is given by:

$$\frac{\sigma(I)}{I} = \frac{2\sigma(V_T)}{(V-V_T)} \qquad (2.1)$$

where V is the gate-source voltage and V_T is the average threshold voltage. The same analysis for mobility gives:

$$\frac{\sigma(I)}{I} = \frac{\sigma(\mu)}{\mu} \qquad (2.2)$$

where $\sigma(\mu)$ is the mobility variation and μ is the average mobility. As the threshold voltage is approached the percentage current variation becomes very large, creating difficulties in displaying low grey levels. The mobility variation remains constant and therefore is less important. To improve this situation various pixel circuits have been devised that aim to compensate for the variations in threshold voltage and mobility. The next section discusses the measurements made on displays constructed with these circuits, all from a single process batch.

3. Measurements of Display Uniformity

3.1 Current Source Display

For the purpose of comparison, uniformity measurements from our current source display are included here in figure 2.

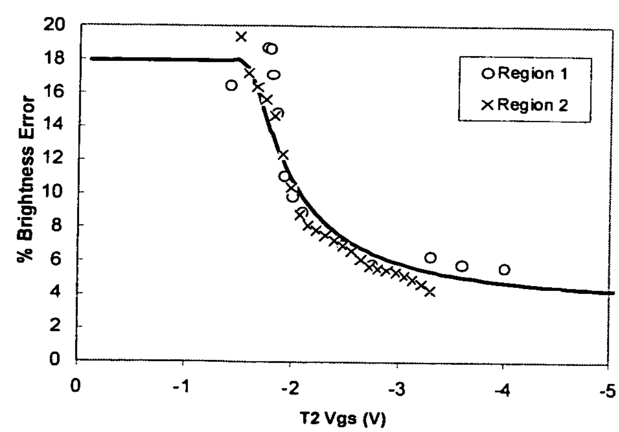

Figure 2 – Current Source Display Uniformity.

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The theoretical curve predicts a threshold voltage variation of 3% and a mobility variation of 4%. This is in reasonable agreement with test structures near this display that show a threshold voltage variation of 4% and a mobility variation of 5%. This data shows that for all gate-source voltages the percentage current variation is well above the required 2%, and becomes large as the threshold voltage (1.75V) is approached, in agreement with equation 2.1. At large gate-source voltages the uniformity is dominated by the mobility variation.

3.2 Digital Display

This option drives the circuit in figure 1 into a digital mode i.e. pushes T2 into its linear operating region. Then the anode of the LED will be connected to the well-defined voltage on the power line in the on state, or at ground when the gate source voltage is set to zero. The disadvantage is that we only have 1-bit per pixel. To achieve grey scales requires Area Ratio Greyscale (ARG) techniques i.e. repeats of the figure 1 circuit for every bit required. Alternatively pulse width modulation can be used i.e. greyscales by time division. A mix of both schemes can also be used. Figure 3 shows the uniformity measurements from our digital display that incorporates 3-bits ARG per pixel.

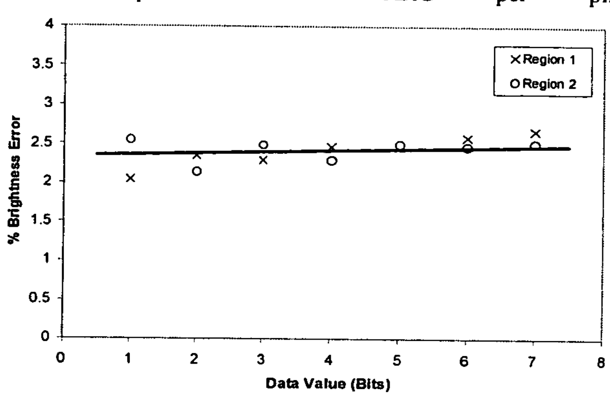

Figure 3 – Digital Display Uniformity

3.3 Threshold Voltage Shift Display

This circuit allows the measurement of the threshold voltage of the current providing TFT at every addressing time [3]. The circuit that we have used is shown in figure 4.

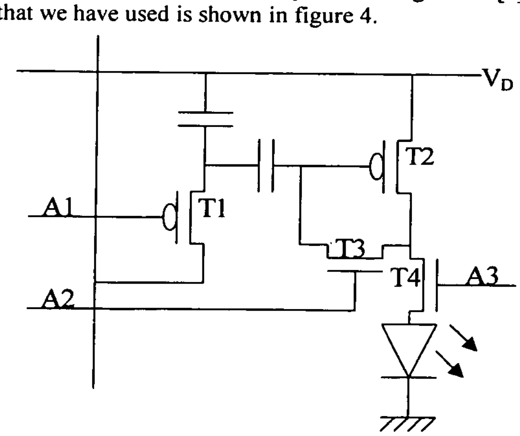

Figure 4 – Threshold Voltage Shift Circuit

The circuit requires three addressing lines to enable the measurement of the threshold voltage and then the addition of the data voltage to create a gate source voltage. The large number of addressing lines reduces the available pixel aperture and the circuit cannot compensate for mobility variations. Figure 5 shows the measured uniformity.

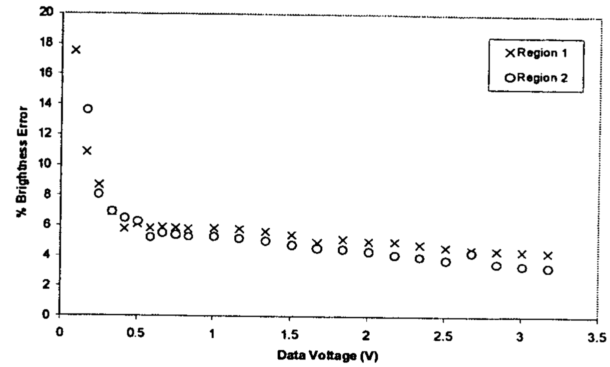

Figure 5 – Threshold Voltage Shift Display Image

3.4 Current Mirror Display

There are several variants of the current mirror pixel circuit [4][5] and our preferred circuit is shown in figure 6. This requires a current sink on the column to address the pixel. The idea is that the current on the column is pulled through the TFT T2 and the gate-source voltage corresponding to this current stored on capacitor C. This circuit, at least to first order, overcomes both threshold voltage and mobility variations. The pulsed cathode approach has several advantages, these are an efficient LED operating point, higher programming currents and improved motion portrayal. Figure 6 shows the circuit and figure 7 shows the uniformity measurements for this display.

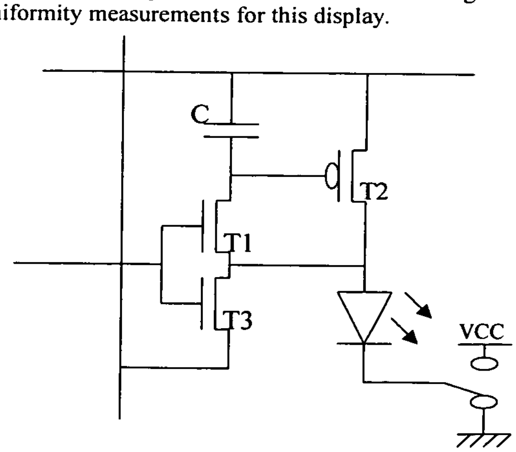

Figure 6 – Current Mirror Pixel Circuit

3.5 Uniformity Comparison

The results shown are measured from displays from the same batch, so that the displays all have similar TFT characteristics. The simple current source pixel gives an error of 5% at high brightness and 20% at low brightness. The uniformity of the digital display is independent of TFT characteristics and the results confirm this showing that the digital display has a very

good uniformity with errors of 2.5%, independent of brightness. The threshold voltage shift display compensates for threshold voltage variations but not for mobility variations, which leads to higher uniformity than the simple current source pixel, especially at low brightness. The current mirror display compensates for both threshold voltage and mobility and so can achieve higher uniformities than the threshold voltage shift display, with a brightness error of approximately 3%.

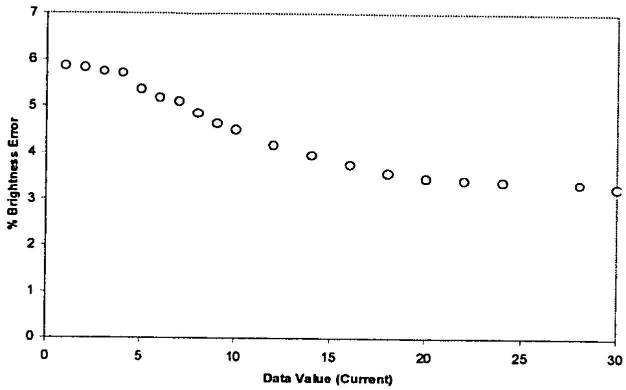

Figure 7 – Current Mirror Display Image

4. Optical Feedback for Differential Aging Compensation

The pixel circuits described so far are open loop in as much as a control signal is used to control light output and there is no feedback of brightness to the pixel circuit. The pixel brightness in these circuits is a function of the driven current and the characteristics of the LED. Non-uniformity in the transistors or LED's results in display non-uniformity. In addition to this, temporal changes in the LED due to degradation cannot be compensated at pixel level and the display will show differential aging artifacts. For these reasons it is preferable to directly control the light output of the pixel. Poly-Si transistors can be used as photodiodes, without extra process complexity, if the gate is made from the ITO layer, and connected to an appropriate node in the circuit to bias the TFT continuously in the off-state. The photodiode can then be used as a sensor to feedback brightness information to the pixel circuit [6].

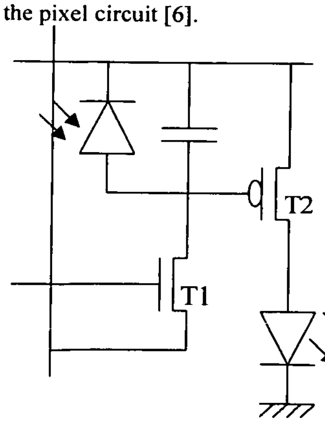

Figure 8 – Optical Feedback Circuit

Figure 8 shows one version of a feedback circuit. This circuit controls the total number of photons emitted from the pixel in one frame period. During the driving period the photo-current from the photodiode discharges the storage capacitor. At any point in time the photo-current is proportional to the brightness of the LED. Whilst the LED is emitting light, the storage capacitor is discharged, until the gate-source voltage of the driving transistor reaches its threshold voltage. The LED then stops emitting light.

Ideally this circuit will automatically compensate for LED non-uniformity and degradation as the number of photons required to discharge the storage capacitor is fixed. The uniformity issues now rest with the opto-coupling efficiency (the gain of the feedback path), and the driving transistor threshold voltage variation.

4.1 Circuit Dynamics

A simple analysis of the circuit in figure 8 shows that the differential equation for the voltage on the storage capacitor is given by:

$$C\frac{dV}{dt} = -\frac{\beta}{2}\eta_P\eta_{LED}(V-V_T)^2 \quad . \quad (4.1)$$

where η_P is the efficiency of the photodiode and η_{LED} is the efficiency of the PLED. η_{LED} will vary very slowly in time because of the PLED aging. In the above equation it is assumed constant in time i.e. the integration period will be very much less than the aging time of the PLED. The standard quadratic law for a MOSFET has been used with β representing the transconductance parameter. Integrating and evaluating the PLED current enables the light-output from the PLED to be found as a function of time. Figure 9 shows this for two pixels with different polymer efficiencies and the same initial gate-source voltage V(0).

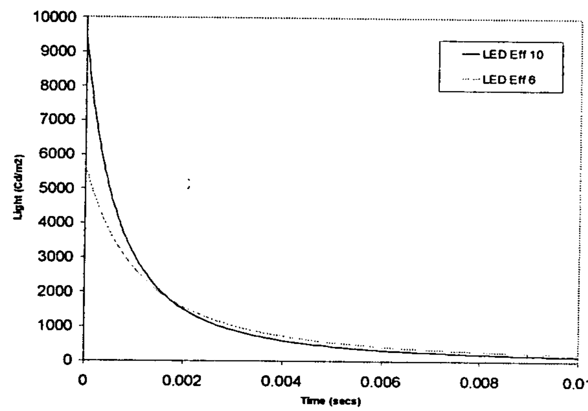

Figure 9 – Light Output for the Optical Feedback Circuit as a function of time from simulations.

It can be seen that the less efficient LED starts from a lower initial luminance and decays more slowly than the more efficient LED. If we now integrate the light output over a frame time we find:

$$L_T = \frac{C}{\eta_P}(V(0)-V_T)^2\left(\frac{T_f/\tau}{T_f/\tau+1}\right) \quad (4.2)$$

where T_f is the frame time and $\tau = 2C/\beta\eta_P\eta_{LED}$ is a time constant. Therefore, if $T_f/\tau >> 1$ we have the total light output in a frame time L_T given by:

$$L_T = \frac{C}{\eta_P}(V(0) - V_T)^2 \qquad (4.3)$$

which is independent of the LED efficiency η_{LED} and therefore the aging of the LED. The above expression contains the threshold voltage so we would expect some image non-uniformity. However, the LED will still emit light when the drive TFT is in its sub-threshold region and therefore (given enough time) will completely discharge the storage capacitor and this will remove the TFT non-uniformity.

4.2 Measurements of the Feedback Display

To illustrate the aging compensation effect in this circuit we 'burnt in' a checkerboard pattern over a long period. We then switched the display into a non-compensating mode where variations in brightness were mainly due to the differential aging. Figure 10(a) shows the display when driven in this mode, a checkerboard pattern is clearly visible. Figure 10(b) shows the display driven normally in its compensating mode. The 'burnt in' checkerboard pattern is now almost invisible.

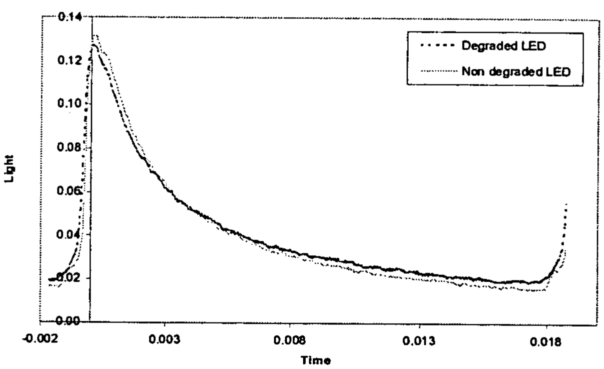

Figure 11 – Dynamic operation of optical feedback circuit.

To further show the dynamic operation of the circuit we measured the light output from an degraded pixel i.e. dim and an undegraded pixel i.e. bright. The traces measured can be seen in figure 11, the young pixel is the grey trace and the old pixel is the black trace. It is clear that the pixel circuit is operating as predicted by theory i.e. figure 9.

5. Conclusions

In this paper we have demonstrated and measured displays with five different pixel circuits for image uniformity and differential aging compensation.

The improved pixel circuits have been shown to give better uniformity, as predicted by simulations. The threshold voltage shift display can offer uniformity improvements when compared to the simple current source pixel by compensating for threshold voltage variations, and the current mirror display can offer further improvements by compensating for mobility variations as well as threshold voltage variations.

In addition the photodiode compensated display has been shown to be operating as expected from simulations and has been demonstrated to reduce the visibility of burn-in in the display.

6. References

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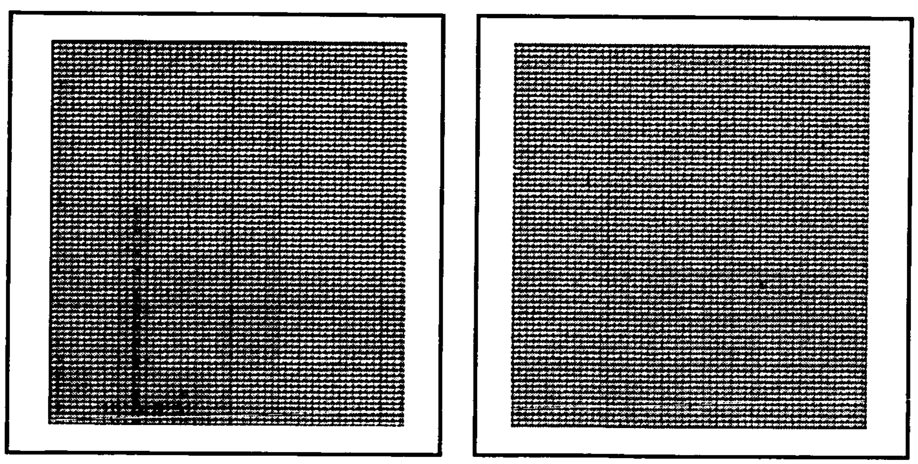

(a) No Compensation (b) Compensation

Figure 10 – Optical Feedback Differential Aging Compensation